National Aeronautics and Space Administration

NASA Exploration Power Distribution Systems

Presented to
S&T Electrical Systems & Wiring Inter-Agency Meeting

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Outline

- Evolution of Human Exploration Power Systems
- Spectrum of Power Systems and Voltages
- Power Quality
- Aerospace Program EPS Development
- – AMPS Modular Power Components
- – AMPS Standardized Modular Power Interfaces

Evolution of Human Exploration Power Systems

EARTH RELIANT	PROVING GROUND		EARTH INDEPENDENT	
Initial Exploration Missions	Extending Reach	Into The Solar System	Exploring Other Worlds	Planetary Exploration

ISS
- Multi-segmented modules
  >200kW
- Multiple assembly flights
- Chemical propulsion (reboost)
- Load shed tables, basically manual ops

Space Power:
- Multi-segmented modules
  >100kW
- Multiple assembly flights
- Electric propulsion dominates
- Manual to semi-autonomous ops

Surface Power:
- Multi-segmented power units
  kW to >10kW each
- Manual to semi-autonomous ops

Space Power:
- Multi-segmented modules
  >300kW to multi-MW
- Multiple assembly flights
- Electric propulsion dominates
- > Semi-autonomous ops

Surface Power:
- Multi-segmented power units
  >10's kW each
- ≥ Semi-autonomous ops


Near Earth Missions

Extended Missions


Mars/Moon Missions

ISS Deep Space & Mars Risk Reduction → *Deep Space Port Mars Preparation* →

Missions: Months
Return: hours

Missions: < year
Return: days

Missions: > years
Return: > months

Spectrum of Power Systems and Voltages

EARTH RELIANT | PROVING GROUND | EARTH INDEPENDENT

Voltage Standards
28Vdc
120Vdc
160Vdc

Solar Arrays
Batteries

Batteries

Solar Arrays
Batteries
Fuel Cells
Surface array
Surface nuclear
(Brayton, Stirling)

Voltage Standards
28Vdc
120Vdc
120Vdc to >300Vdc (electric propulsion)
AC distribution for Brayton or Stirling

Voltage Standards
28Vdc
120Vdc
>300Vdc (electric propulsion)
AC distribution for Brayton or Stirling

★ Major issue with Rad Hard Components

Solar Arrays (0.8 – 2AU)
Nuclear
Batteries
Flywheels
Super-Capacitors
Surface Fuel Cells
Surface array
Surface nuclear
(Brayton, Stirling)

Complexity and International mix makes it imperative to develop comprehensive power quality standards from the beginning

What is Power Quality?

By Wikipedia –

In its broadest sense, power quality is a set of boundaries that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electrical power that drives an electrical load and the load's ability to function properly with that electric power. Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all.

Power Quality Lessons

- Historically space power systems requirements have been unique for every platform
  - Roadblock for re-use of equipment and standardization
- Majority of the existing power quality specifications were developed for engine driven alternators for aircraft with AC transformers and rectifiers for DC.
- Space power systems consist of solar arrays, electrochemical systems, thermal electric generators, etc.
  - All these sources have unique characteristics
- Spacecraft loads are often designed for unique platforms
  - Adapted to meet unique voltage ranges and power quality characteristics
- Common standard allows transportability to a new platform with high confidence for minimal requalification
- Achieve reliability through verification
  - ISS had remarkable success - Pre-assembled flight elements never tested together were attached to each other for the first time on-orbit and worked

Characteristics of a Power Quality Standard

- Address both Sources and Loads
- Provide a load and source characteristic for proper operation and protection
- Provide requirement rationale to clarify intent
- Provide verification approach for each requirement
- Provide typical test procedures
- Allow for design flexibility
- Clearly describe interface (connection) power for loads
- Specific specifications can then be developed and coordinated using the Standard

We now have SAE AS5698 Power Quality Standard

Standard addresses Power Quality for 28 and 120 Volt DC

Source Requirements

- Steady State Voltage Range
- Transient Voltage
- Ripple Voltage
- Stability
  - Stability Criteria
  - System Impedance
- Power Isolation
- Common Mode Noise
  - Voltage
  - Current
- Inrush Surges
- Reverse Current
- Fault Clearing
- Fault Coordination

Load Requirements

- Operating Voltage Range
- System Voltage Transients
- System Ripple Voltage
- Stability
  - Stability Criteria
  - Load Input Impedance
- Input Isolation
- Common Mode Noise
  - Voltage
  - Current
- Limiting Inrush Surges
- Limiting Reverse Current
- Overloads

Aerospace Program for EPS Development

Advance Exploration System (AES) Program
AES **M**odular **P**ower **S**ystems
(**AMPS**) Project

Advanced Exploration Systems (AES) Program
AES Modular Power Systems (AMPS) Project

Objectives:

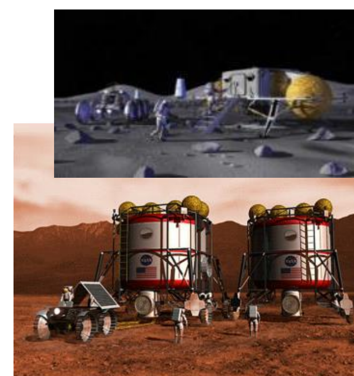
- Develop modular power units which, when combined with standardized interfaces, can provide commonality across a variety of exploration vehicles.

- Infuse new technology into power systems and components, and prove their capabilities in exploration-based ground demonstrations

Applications

Exploration Missions

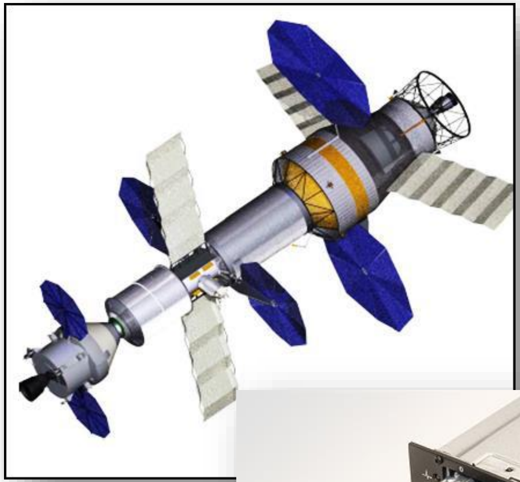
Mars / Lunar Rovers



Planetary Outposts

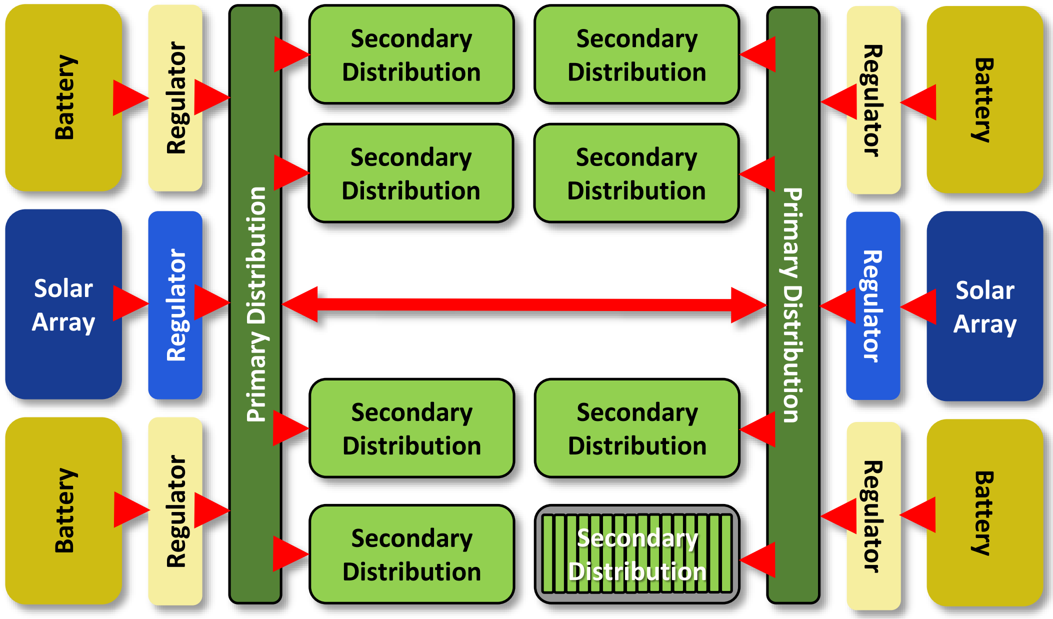
EVA Suits

Why modular?



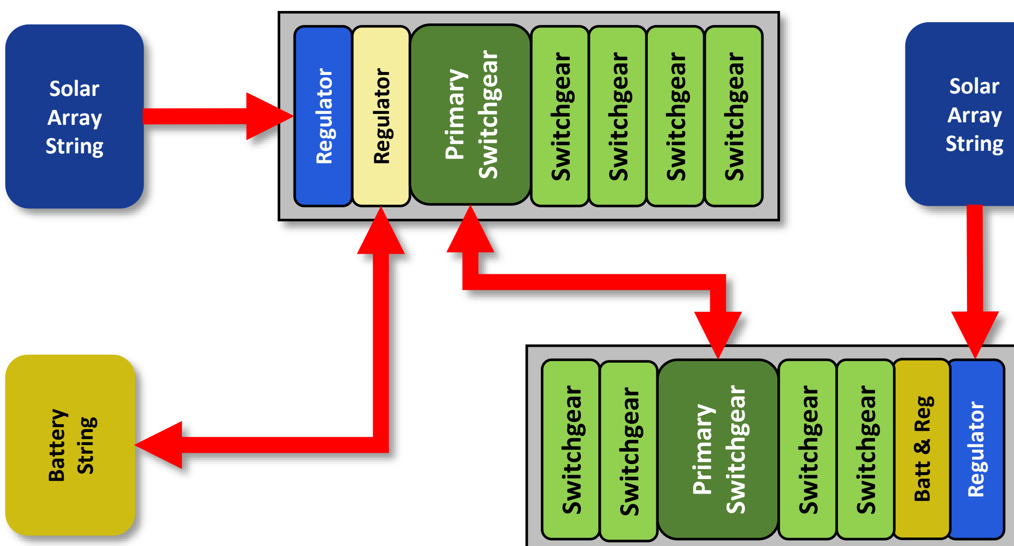
- Deep Space Missions require lower logistic costs
- Reusability
  - Interchangeability between multiple platforms/missions
  - Reduced spare components needed
  - Scavenging components from retired platforms
- Flexibility
  - Scalable for a wide range of architecture sizes/power levels
  - Spectrum of architectures from centralized to distributed
- Reliability
  - Failures cause reduced capability, not complete loss of use
  - Hot-swap replacement minimizes down-time & system effects

General Hierarchical Architecture



"Monolithic" units can be replaced by sets of common modules

Flexible/ Distributed Architecture



PMAD units containing mixed modules enable distributed architectures

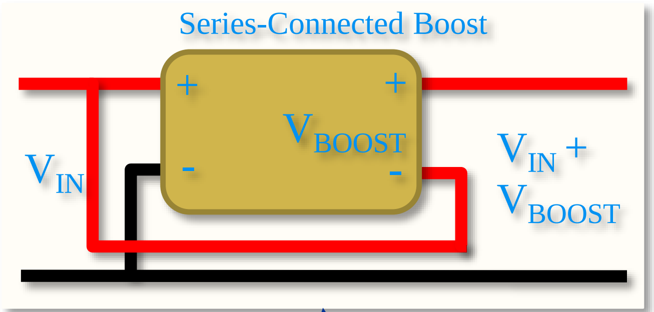
Modular Component Development

- Prototypes will drive development of modular standards.
- Batteries and solar cells are already “modular”, so the next step is to develop modular PMAD components:
- Switchgear features:
  - Remote control
  - Fault containment: current limit and trip
- Converter features:
  - Source/storage/interface/bus regulation
- Common features:
  - Parallelable to grow in power (“tiers” may be required)
  - Digital control, enabling:
    - Intelligent control / automation at the module level
    - Master-less communication for “swarm” intelligence

Solar Array Regulator Development

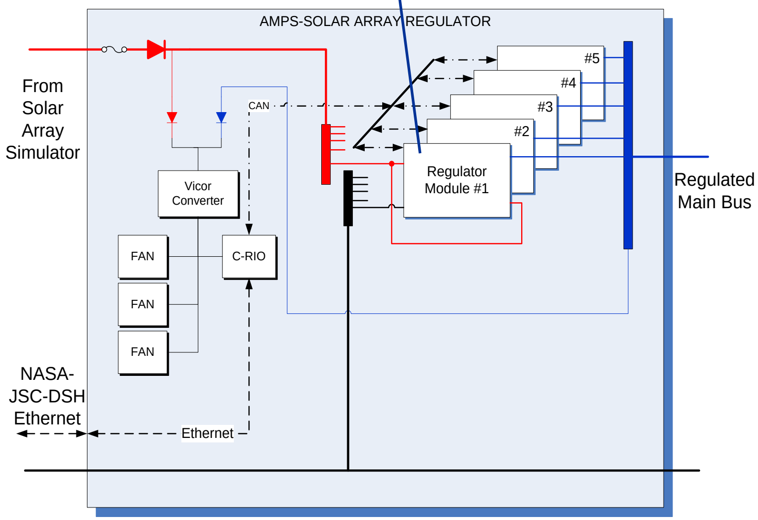
Objective:

- Demonstrate 5kW 120V Solar Array Regulator (SAR)

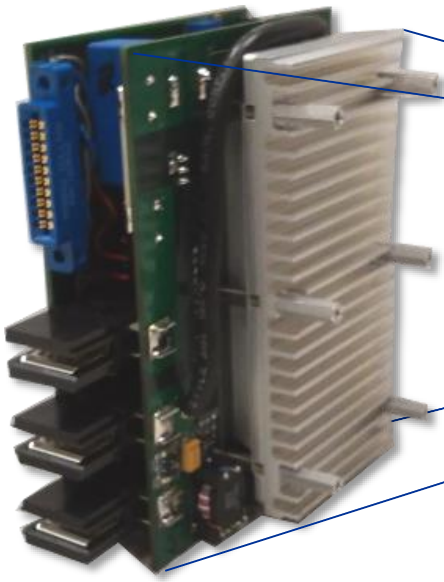


Current Implementation:

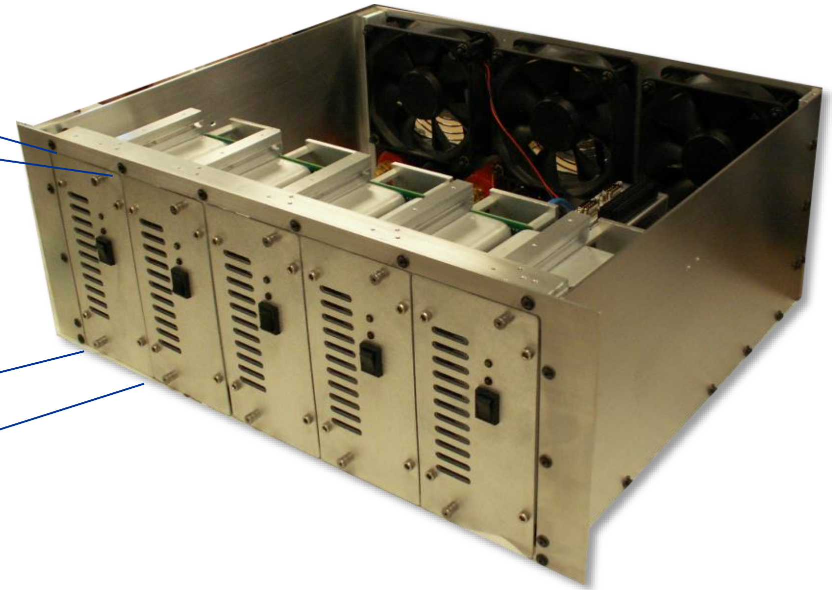
- COTS 120V-to-28V converter
- Series-connected boost configuration: 1kW/module
- Digital control (microcontroller)
  - CAN communication (master-less)
  - Remote control/fault simulation
  - Telemetry
  - Dynamic output voltage set-point (battery charging)
  - Intelligence: efficiency optimization
- Hot-swappable enclosure



Solar Array Regulator Development



1 kW Module

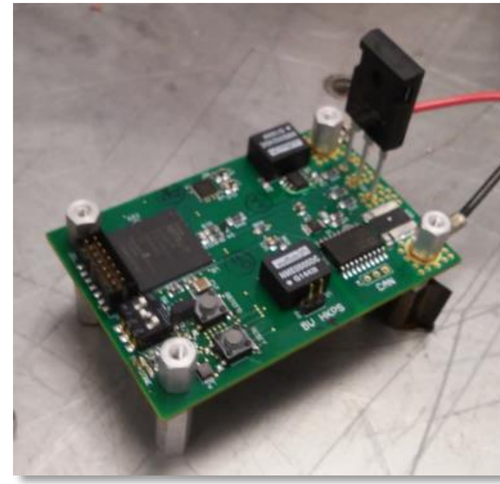


5 kW Unit

- Current Status:
  - Operating in exploration systems controls lab at JSC
  - Regulates bus voltage and bus-tied battery charge current

- Future Work:
  - Replace power stage with custom bidirectional module
  - Replace microcontroller with FPGA

Switchgear Development

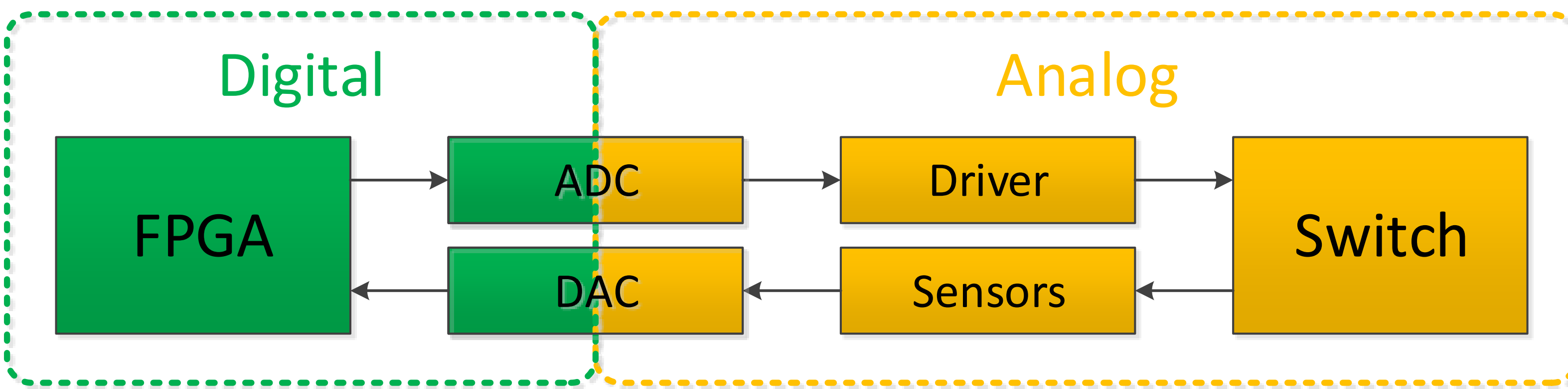


Objective:

Demonstrate a digitally controlled remote power switch emulating the characteristics of the state-of-the-art

Implementation:

- 1200V/42A MOSFET & shunt
- ADC (sensor) & DAC (driver)
  - High speed
  - Non-pipelined (low prop. delay)
- FPGA
  - CAN communication
  - Telemetry
  - Current limiting
  - Thermal trip (power-time curve)



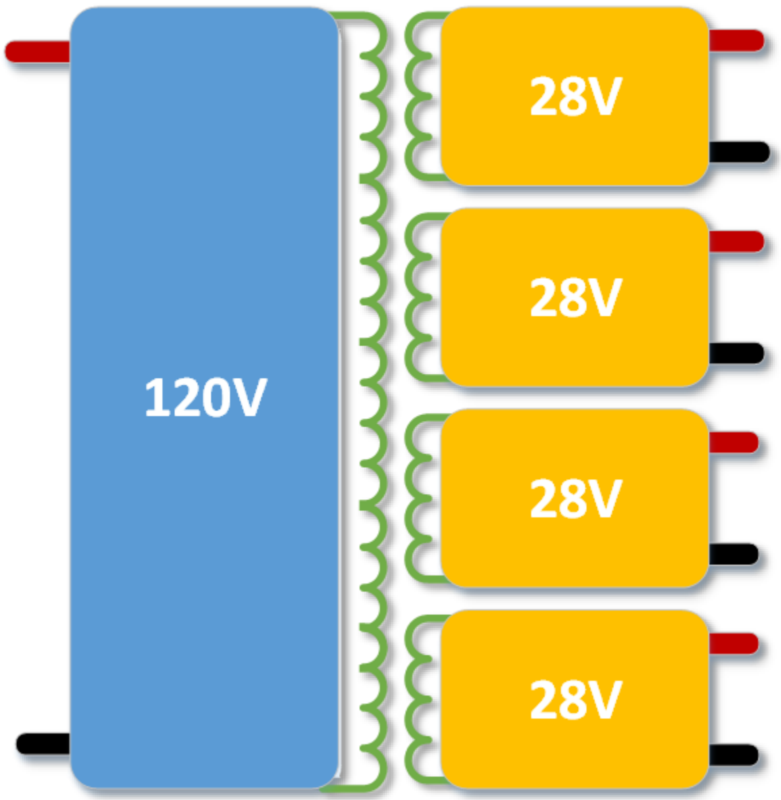
Bidirectional Converter Development

Objective:

- Demonstrate a 1kW multifunction bidirectional converter
  - Battery charge/discharge control
  - Spacecraft interface converter
  - Solar array regulator
  - Bus/point-of-load converter

Implementation:

- 120 V_{IN}, configurable output:
  - 4 outputs in series: 8.3A @ 120V
  - 4 outputs in parallel: 35.7A @ 28V
- Modules can be paralleled
- Topology
  - Forward: Full bridge
  - Reverse: Weinberg/flyback
  - Isolated



Modular Power Components Summary

- The AMPS project is developing and demonstrating modular power system concepts for deep-space human exploration missions.

- Modular power components enable scalable and flexible power system architectures.

- Three prototypes are in development to assist in developing modular power standards:
  - Solar array regulator (5x1kW modules @ 120V)
  - Switchgear (current-limiting to 4A @ 120V)
  - Bidirectional converter (1kW @ 120V/4x28V)

AMPS Standardized Modular Power Interfaces for Future Space Explorations Missions

AMPS Standardized Modular Power Interfaces

AMPS is drafting a proposed standard that is:

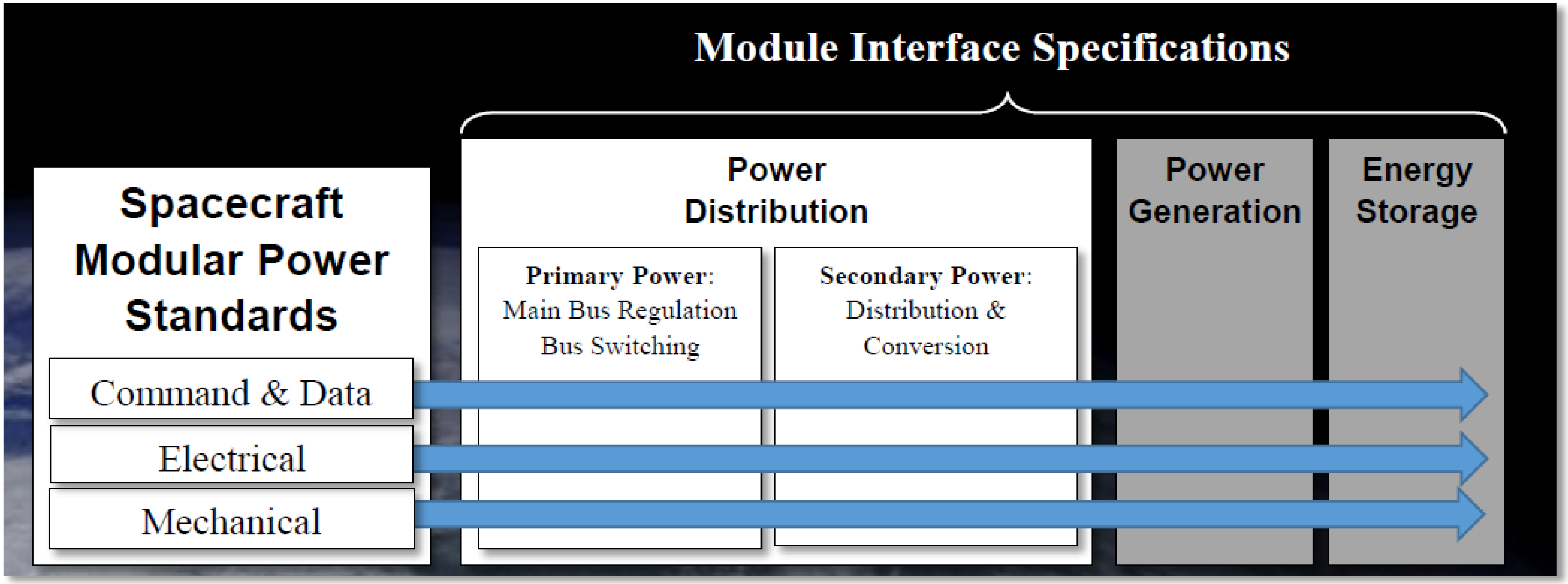
- Applicable to NASA exploration,
- Accommodates variations in power architecture
- Supports mission flexibility (configuration changes)
- Defines the common infrastructure needed to support the modular design
- Standardizes Data, Electrical and Mechanical Interfaces

The intent is to guide power system developers without restricting design or technology options.

- Adopts existing standards where applicable
- Emphasize Interchangeability and Interoperability

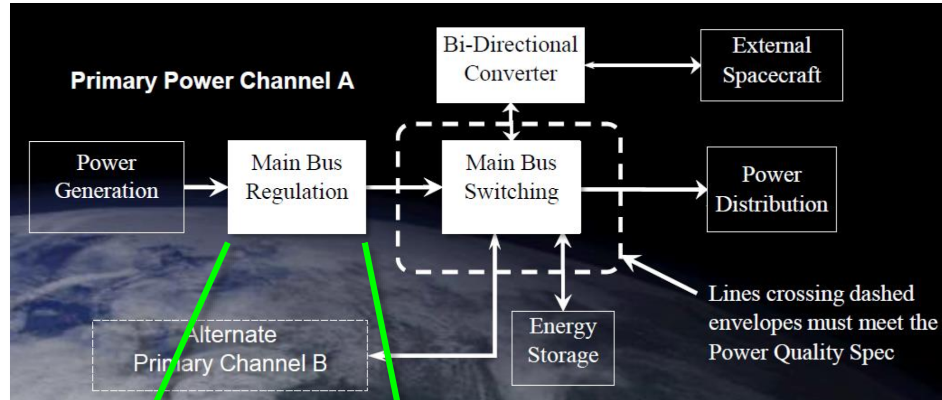
AMPS Standardized Modular Power Interfaces

- Establish a common framework for Data, Electrical, Mechanical interfaces.
- Apply the Standards to 3 segments of a Power Architecture
- Define interfaces between modules and internal to modules
- Create Interface Specs for
  - Assemblies,
  - Subassemblies
  - Components



Standardization Frameworks

- Electrical Interface section addresses modular approach that is flexible, configurable, and supportable
  - Breaking an architecture into functional blocks
  - Grouping functions as common modular elements
  - Creating an interconnection framework of Common Backplanes
  - Defining the characteristics that make up Modular Interface Specs

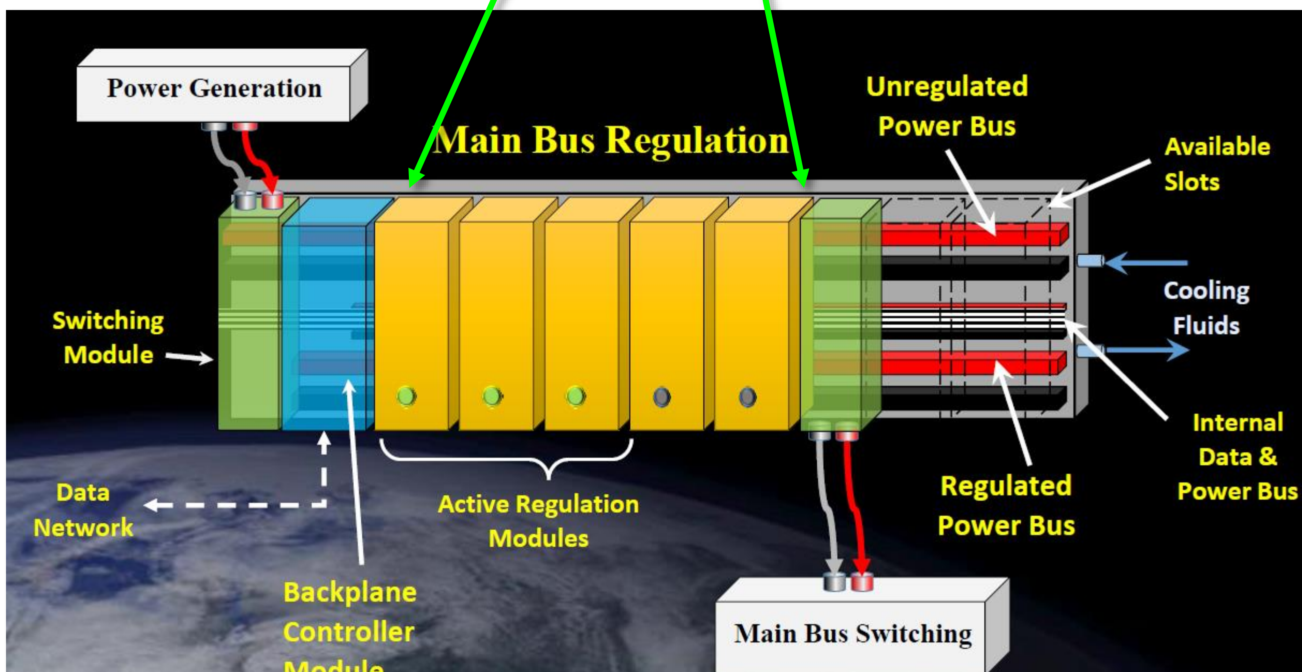


Primary Power Regulation Backplane-Module

Modules mounted on a Assembly Level Backplane.

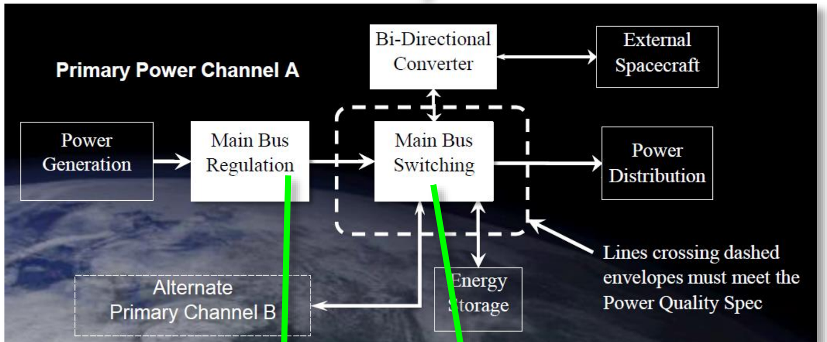
Unregulated & Regulated Power, Data and Structural and Thermal Interfaces

Modules: Switching, Regulation, Unit Control

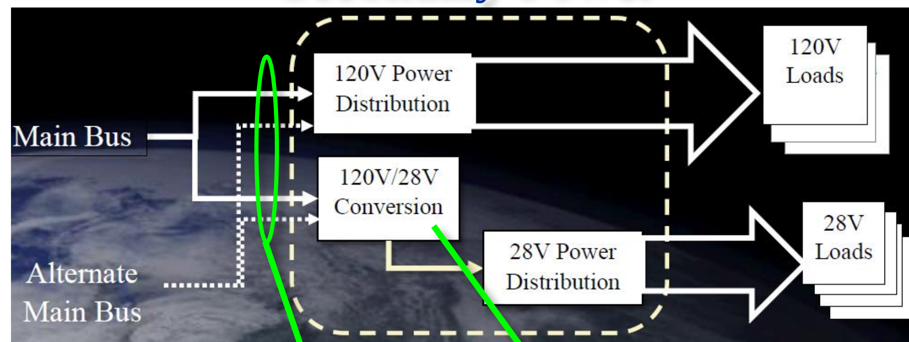


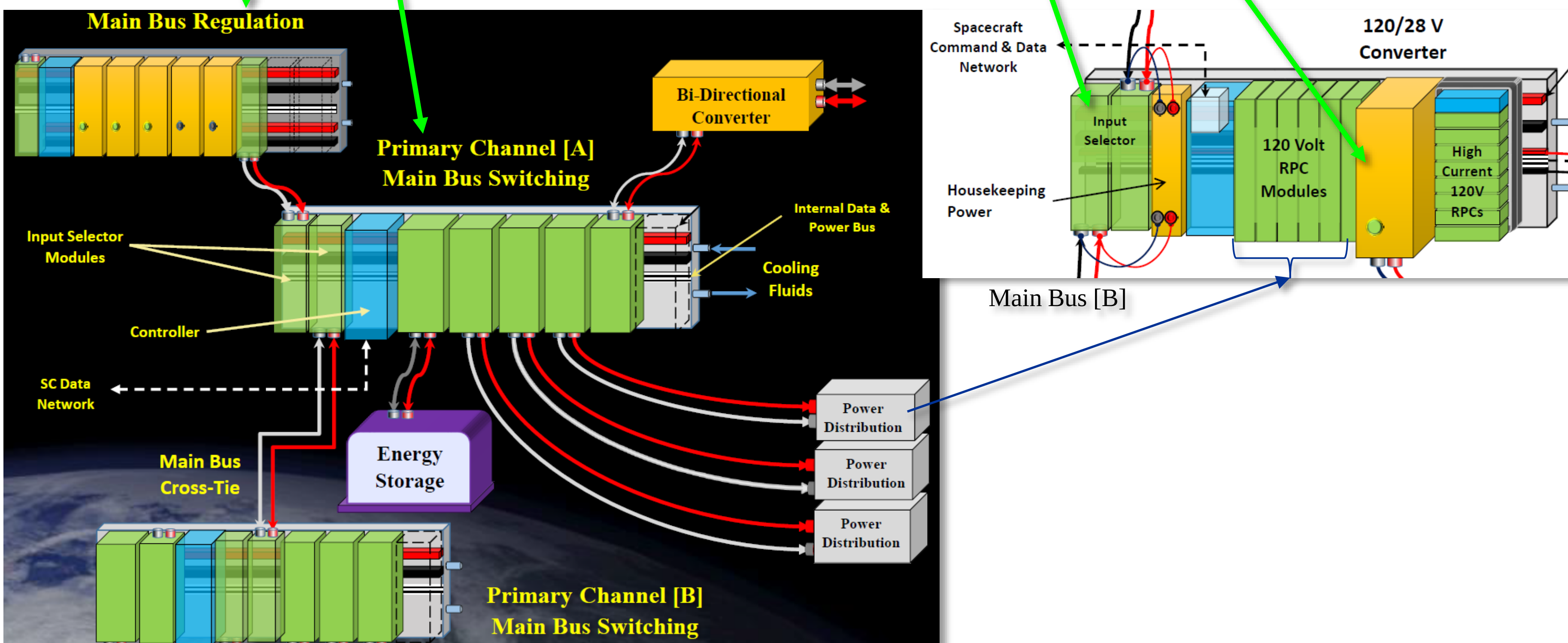
Power Assembly Backplanes-Modules

Primary Power



Secondary Power





Additional Standardization Frameworks

- Command & Data Interface section addresses the Communication protocols and Software with emphasis on interoperability standards.
  - Power modules will support automatic ID, Digital Configuration and Integration. (i.e. Plug-and-Play)
  - Internally, modules adopt protocols suited power applications but must support the higher level Interoperability requirements.

- Mechanical Interface section addresses the mechanical needs in terms of structural support, encapsulation and thermal control.
  - Modules and backplanes must support static and dynamic loads while providing a means of transferring thermal loads.
  - Mechanical interfaces must assure ease of access and interchangeability.

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